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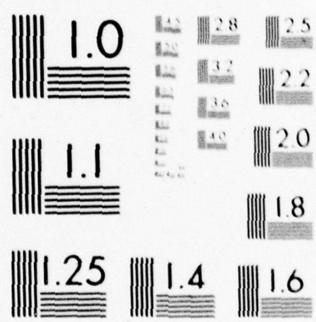

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TECHNICAL REPORT 7615 FINAL

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MEASUREMENTS AND ANALYSIS OF THE FORCES ACTING ON A SMALL AIRCRAFT FLYING IN THE UPWASH OF A LARGE AIRCRAFT

By

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Prepared for

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I. INTRODUCTION

A study has been made of the forces and moments acting on a small aircraft while it is flying in the upwash field adjacent to and behind the wing tip of a larger airplane. Preliminary analysis of the expected ranges of forces and moments were made using available theoretical methods and confirming experiments were performed in the HYDRONAUTICS Ship Model Basin (HSMB®). The tests utilized a large model of the Boeing 747 transport aircraft and a smaller model typifying a fighter type aircraft. The range of positions of the small model relative to the large model extended laterally 30 full-scale feet from the wing tip or from the tip vortex and downstream roughly 80 feet behind the wing tip. Consideration was given to the problem of maintaining steady position at a point that provided a maximum increase in the lift to drag ratio of the small aircraft.

The present study was undertaken to provide information on the improved range and endurance to be obtained by small aircraft, RPVs or drone missiles if they make use of the favorable upwash field generated near the wing tip regions of larger aircraft, transports or bombers. The phenomenon is well known and was observed first in the flying of geese. Theoretical explanations were prepared by Schlichting[(1)] and earlier, Munk's brilliant "stagger theorem"[(2)] showed the advantage in reduced drag due to lift that accompanied the flight of multiple aircraft with other than tandem positional arrangements. Donaldson[(3)] has studied the general problem of aircraft obtaining increases in range by flying in the wake of other aircraft, and Donaldson, et al.[(4)] have considered the problem of an aircraft operating in the upwash field of two leading aircraft.

The present report provides a description of the test facilities, models, data reduction system and test procedures.

Data are presented for a model configuration not equipped with ailerons for trimming out rolling moments; however, an analysis section is included to supplement the data by including computations for the trimmed conditions. Finally, conclusions are presented together with recommendations for needed additional research.

II. DESCRIPTION OF TEST EQUIPMENT AND PROCEDURES

Tests were conducted in the HYDRONAUTICS Ship Model Basin (HSMB®), a facility 430 ft. long, 12 ft. deep and 24 ft. wide. The use of water as a test medium is justified for Mach numbers of flight below about 0.3 and documentation for this use is given in Reference 5. Extensive use has been made of this facility by the NASA for studying hazards of wake turbulence[6]. Both aircraft models were mounted on a carriage and towed at a speed of 18 ft/sec. Forces and moments were measured on the two aircraft; however, only lift, drag and pitching moments were obtained for the larger aircraft model. These readings were obtained using uniaxial variable-reluctance force gages in series whereas the small aircraft was fitted with a six-component, Strain-gauge Balance. Raw unprocessed data was recorded on magnetic tape and subsequently processed automatically using the data reduction system of the HSMB.

Photographic data were also obtained to define the position of the wing tip vortex shed from the large wake generating aircraft model. For this, dye was injected at the wing tip and the marked vortex was photographed from two positions. The location of the vortex relative to the wing tip was then determined by stereo triangulation. Positional references were obtained from grids placed on the wall and floor of the towing basin that was illuminated by underwater lights (see Reference 6).

The two models used are shown in Figure 1. The large model is an accurate 0.03-scale reproduction of the Boeing 747 transport. It has a wing span just under six feet and was flown in the cruise configuration at a lift coefficient of 0.6. The engine nacelles are simulations with simple streamlined rings; no power is provided. The small model is a generalized configuration having wing sweepback and geometry approximately that

of a fighter aircraft or perhaps a drone. Dimensions of both models are given in Table 1. As seen in Figure 1 the large model is supported from the towing carriage by means of two streamlined struts entering the model at the top and in line with the vertical tail. The small model is supported from the rear on a sting in a manner typical of wind tunnel strain-gauge-balance practice. The sting is in turn supported by a single streamlined strut that can be moved laterally and vertically to position the model at any position relative to the wing tip of the large model. The angle of attack of the model is changed by rotation of the entire strut-model system about a horizontal axis on the towing carriage structure.

Test runs were made with the small model in various positions behind and adjacent to the wing tip of the large model. Angles of attack of the small model were varied to encompass the highest lift to drag ratios. Suitable waiting periods between runs were allowed to permit quieting of the basin water and data taken were averaged over time periods of about 10 seconds (180 ft. of run). The wing mean chord Reynolds numbers were 1.5×10^6 for the Boeing 747 and 6×10^5 for the simulated fighter model.

The accuracy of the data is considered adequate for the engineering study being made but is not as high as usual for tests of this kind for two reasons: (1) the six-component balance sensitivity was quite low for most of the readings because it had been designed for the high loads expected with a direct encounter of the small aircraft model with the tip vortex, and (2) the turbulence in the water tank generated a certain amount of noise in the signals that made for larger standard deviations of the readings than would have been obtained from static calibrations of the measurement system. The readings of the lateral force and yawing moment were the most severely affected and these readings are omitted from the data because of excessive scatter.

III. TEST RESULTS

The tests were conducted for a matrix of angles of attack and position of the small model relative to the large model. Figure 2 shows top and side views of the models and the various positions at which data were obtained. At each position the vertical height and angle of attack of the small model was varied. The distances shown correspond to a full-scale situation in which the large aircraft is the Boeing 747 transport or another of equal wing span. The closest approach of one aircraft's wing tip to another is ten feet.

The tip vortex location, also shown on Figure 2, was determined from stereo photographs of the dyed cores of the tip vortices. A typical photograph of the dyed vortex against the ruled background of the test range is presented in Figure 3 and Table 2 gives values of the vortex displacement as a function of downstream distance from the tip. Accuracy of the vortex position is estimated to be within plus or minus two feet at full scale. The vortex at these short distances downstream from the wing tip was found to be quite stable.

Compilation of Data

Table 3 presents a compilation of the data obtained. Moment values are taken relative to the point on the body centerline at the one-quarter chord position of the wing mean aerodynamic chord.

The lift to drag ratio data are summarized on Figure 4. The solid drawn lift to drag ratio curves at the various mean upwash angles are prepared from the basic zero upwash data by a simple resolution of the force vectors at the various upwash angles assuming the upwash angle to be uniform. The equation for the curves is:

$$L/D = (L/D)_o \left[\frac{1 - (D/L)_o \tan E}{1 - (L/D)_o \tan E}\right] \quad [1]$$

where $(L/D)_o$ is the lift to drag ratio in the free air outside the upwash region and ϵ is the assumed uniform upwash angle. For the small ϵ angles of interest the lift coefficient is essentially unchanged. The data bunch reasonably about the lines of constant angle of attack and indicate that mean or "effective" angles of upwash of over 2 degrees are experienced. As will be demonstrated later on, the mean upwash angles experienced are in good agreement with expected values.

The maximum lift to drag ratios are found at the closest approach to the vortex as expected. Referring to Figure 2, the x-wise positions of the maximum values are at 25 and 75 feet; the highest value measured was 13.4 representing a 50% increase in lift to drag ratio over that of the free model.

The rolling moment coefficient was also found to be maximum at the highest lift to drag ratio, a value of 0.021 being the highest value reached. This is a value easily neutralized by the ailerons on typical aircraft, more will be discussed on this question in a subsequent section.

The vertical location of the following aircraft relative to the wing tip of the large aircraft has a definite effect on the lift to drag ratios achieved; highest values appear to occur with the smaller aircraft below the vortex at heights less than ten feet (full scale).

Pitching moment coefficient data shows a substantial scatter but the effect of the upwash field is primarily related to the increased angle of attack and hence increased lift coefficient.

IV. ANALYSIS OF THE DATA

The models were not equipped with ailerons or other moveable surfaces and it is pertinent to ask what changes in lift to drag ratio would be incurred if the small model were trimmed. The largest effect would be expected from the out of trim rolling moment and calculations have been made to find the amount of aileron deflection required for trim and to determine the additional drag and yawing moment incurred at the trimmed condition. The first step involves the estimation of the wake induced upwash distribution. In Figure 5 are drawn three relevant curves, the lowest is the upwash adjacent to an elliptically loaded wing of aspect ratio 7 and C_L of 0.6. The second is the upwash produced by the same wing but downstream many span lengths and with the assumption that the vortex sheet does not roll up. The third and highest curve is the upwash field far downstream completely rolled up and calculated by the Betz approximation[7]. It is unfortunate that time did not permit calculation of the upwash fields; however, it is expected that the upwash would rapidly adjust from the $x = 0$ values shown to the Betz values at distances of several spans downstream.

It can be seen that upwash predictions in the vicinity of the mid-span point of the small aircraft wing vary from values of 1 to over 2° as the aircraft approaches the vortex. The low values shown at $x = 0$ indicate that flight close behind or adjacent to the 747 wing tip is not favorable for obtaining high lift to drag ratios. For preliminary trim estimates the upwash values shown for the intermediate curve were used with a lifting-line technique as modified by Kucheman[8] to compute span load distributions at two geometric angles of attack. The values taken were those in Figure 5 above the bar labeled "model wing span" and represent values for the case where the small aircraft

wing tip is at the same vertical level as the vortex and 10 feet away laterally. The computed span loadings are shown in Figure 6 as the solid curves; the asymmetry of the loadings is obvious and the computations predict a rolling moment coefficient of 0.006. To include the effect of ailerons it was assumed that ailerons having a span of 30% of the wing semi-span and a chord of 20% of the local wing chord were deployed. The aileron deflections were introduced into the lifting line theory by assuming that two degrees of aileron deflection was equivalent to one degree of wing chord angle of attack change. This result is justified by the NACA data shown in Figure 7 which is taken from Reference 9. The amount of aileron deflection needed to neutralize the induced rolling moment was determined using the lifting line theory and the resulting final span loadings with ailerons deployed are shown on Figure 6 as the dashed lines. For this case the aileron deflection required was estimated to be about $3\frac{3}{4}$ degrees.

The additional drag produced by the aileron deflection was estimated by means of the lifting line theory and plots of spanwise distribution of drag due to lift are presented in Figures 8a and 8b. It is seen that the vortex induced upwash field overpowers the downwash induced by the trailing vortex system so that the net drag due to lift is negative. It is less negative at 5° angle of attack than at 3.3° and the change in drag with aileron deflection is small. The numerical results for the 3.3° case show an increase in drag due to lift for the aileron deployment of only 0.00012, a truly negligible effect.

The distribution of induced drag along the span of the wing tends to produce a yawing moment; however, computation of this effect for the distributions of Figures 8a and 8b indicate that the induced yawing moment coefficient would be roughly .001, a negligible value. Actually the profile drag changes

due to aileron deployment may be of greater significance but the test data, though of poor accuracy, showed no sizeable yawing moments produced by the vortex field.

V. DISCUSSION OF RESULTS

The investigation described here must be considered preliminary; nevertheless, the experimental finding of a 50% increase in lift to drag ratio for a small fighter-type aircraft flying off and behind the tip of a larger transport or bomber aircraft is significant. Substantially higher increases in lift to drag ratio for the same relative aircraft positions would result if the smaller aircraft were of higher preformance, that is, the present small model achieved a maximum L/D of only 8.9 in free flight whereas for an aircraft having the aspect ratio of the model should have a lift drag ratio of nearly 12. The reason for the poor performance of the model in the present tests is not known but may be the result of excessive interference drag because of the relatively large fuselage. The incremental drag rise due to lift was nearly twice that expected for clean aircraft configurations. It can be estimated from Equation [1] that a small aircraft achieving a reasonable L/D of 14 would have its maximum L/D increased by about 100% if it flew in an upwash of 2°.

The maximum range of the small aircraft would generally be increased in proportion to the L/D ratio achieved. This follows because the characteristics of modern turbo-jet engines are such that at given altitude and speed conditions the thrust specific fuel consumption is constant over rather large variations in thrust. Control of the small aircraft over the extended periods needed for range extension would require the development of a suitable autopilot slaved to sensors capable of sensing the position of the following aircraft relative to the large aircraft. No influence of the small aircraft on the large should be felt because the most favorable locations for the small aircraft are well behind the wing tip of the large aircraft. The

ratio of lift coefficients for the two aircraft would be fixed by the ratio of the wing loadings. On the other hand, the lift coefficient for maximum lift to drag ratio would be set according to simple theory by the relation:

$$C_{L_{optimum}} = (C_{D_o} \pi A e)^{\frac{1}{2}} \qquad [2]$$

where C_{D_o} is the basic profile drag coefficient of the airplane, A is the aspect ratio and e the efficiency factor usually found to be about 0.8 to 0.9. To obtain the full benefit of the L/D increases discussed, the lift coefficients of each aircraft must be close to the optimum value. The two constraints mentioned are not usually difficult to meet as the optimum lift coefficients of fighters and bombers are generally close as are the wing loadings. It is clear, however, that each case comprising a pair of aircraft must be considered on its own.

VI. CONCLUSIONS

It has been shown by model tests that an increase of 50% in lift to drag ratio can be obtained by a small fighter-type aircraft flying close to the tip trailing vortex of a larger aircraft such as the Boeing 747. For higher performance aircraft, lift to drag ratios possibly twice the free air values could be achieved; thus enabling ferry-type operations at up to twice the normal range of the fighter aircraft. In the tests described the ratio of the spans of the following aircraft to the vortex generating aircraft was 0.2; for smaller ratios more favorable results should be anticipated so that small turbo-jet drones flying in the upwash fields of bombers might achieve even higher range extensions than noted above. Calculations made for the models tested indicate that control power of typical fighters would be sufficient to maintain level flight in the favorable positions close to a tip vortex.

LIST OF SYMBOLS

α	Angle of attack
c_{mac}	Mean aerodynamic chord
c	Local wing chord
b	Wing span
c_d	Section induced drag coefficient
C_D	Airplane drag coefficient - D/qS
C_{D_i}	Wing drag due to lift coefficient
C_L	Airplane lift coefficient - L/qS
C_M	Airplane pitching moment coefficient M/qS
c_ℓ	Section lift coefficient
C_ℓ	Airplane rolling moment coefficient
D	Airplane drag force
e	Wing efficiency factor
ϵ	Mean upwash angle
L	Airplane lift force
M	Airplane pitching moment
q	Dynamic pressure - $\frac{1}{2}\rho V^2$
ρ	Air density
S	Wing area
V	Flight speed
x	See Table 1
y	See Table 1
z	See Table 1

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Table 1

Geometric Characteristics of a Boeing 747 and Simulated Fighter Models at 0.03 Scale Ratio

	Boeing 747	Fighter
Wing:		
Span, ft (m)	5.87 (1.79)	1.17 (0.356)
Mean Aerodynamic Chord	0.82 (0.25)	0.34 (0.100)
Root Chord	1.64 (0.50)	0.44 (0.134)
Tip Chord	0.40 (0.12)	0.127(0.039)
Sweepback at quarter chord, deg.	37.5	45.0
Area, ft^2 (m^2)	4.95 (0.46)	0.352(0.0327)
Aspect Ratio	6.96	3.87
Fuselage:		
Length	6.76 (2.06)	1.36 (0.415)
Maximum Diameter	0.64 (0.19)	0.187(0.057)
Horizontal Tailplane		
Span	2.17 (0.66)	0.563(0.172)
Area	1.32 (0.12)	0.088(0.0082)
Aspect Ratio	3.6	3.6
Vertical Tailplane		
Height (above fuselage)	0.96 (0.29)	0.216(0.0658)
Area	0.22 (0.02)	0.0376(.00349)

Table 2

Measured Vortex Positions

Distance Behind Wing Tip - ft.	0	25	80	120
Distance Above Wing Tip - ft.	0	0.44	1.40	2.10
Distance Inboard of Wing Tip - ft.	0	4 to 7	13-15	21-23

Table 3

Compilation of the Data

No.	α^o	x	y	z	C_L	C_D	L/D	C_ℓ	C_M
1	5.17	0	10	-10	0.415	.0425	9.8	.0090	- .081
2		0	10	0	0.402	.0430	9.3	.0077	- .076
3		0	10	+10	0.367	.0410	9.0	.0054	- .063
4		0	20	+10	0.349	.0390	8.9	.0051	- .063
5		0	20	0	0.356	.0390	9.1	.0055	- .061
6		0	20	-10	0.358	.0380	9.4	.0057	- .061
7		0	30	-10	0.332	.0370	9.0	.0042	- .055
8		0	30	0	0.347	.0400	8.7	.0038	- .069
9		0	30	+10	0.333	.0370	9.0	.0026	- .057
10		0	10	-10	0.385	.0400	9.6	.0084	- .075
11		25	10	-10	0.374	.0350	10.7	.0090	- .057
12		25	10	0	0.395	.0410	9.6	.0077	- .061
13		25	10	+10	0.358	.0370	9.7	.0059	- .058
14		25	0	+10	0.367	.0380	9.7	.0059	- .052
15		25	0	0	0.395	.0360	11.0	.0095	- .052
16		25	0	-10	0.462	.0430	10.7	.0167	- .091
17			D A	T A	G	A R	B L E	D	
18		25	21.7	+10	0.348	.0370	9.3	.0058	- .055
19		25	21.7	0	0.352	.0380	9.3	.0064	- .057
20		25	21.7	-10	0.349	.0370	9.4	.0064	- .056
21		75	-5.6	-10	0.485	.0440	11.0	.0154	- .086
22			D A	T A	G	A R	B L E	D	
23		75	-5.6	+10	0.378	.0390	9.7	.0061	- .057
24		75	-5.6	-14.4	0.454	.0410	11.1	.0103	- .078
25	3.3	75	-5.6	+10	0.287	.0270	10.6	.0057	- .042
26		75	-5.6	0	0.325	.0260	12.5	.0103	- .047
27		75	-5.6	-10	0.374	.0280	13.4	.0212	- .074
28		75	-5.6	-14.4	0.334	.0280	11.9	.0116	- .059
29		25	0	-14.4	0.316	.0250	12.6	.0096	- .061
30		25	0	-10	0.362	.0270	13.4	.0199	- .073
31		25	0	0	0.312	.0270	11.6	.0080	- .054
32			D A	T A	G	A R	B L E	D	
33		25	10	10	0.267	.0270	9.9	.0047	- .043
34		25	10	0	0.275	.0250	11.0	.0060	- .042
35		25	10	-10	0.269	.0230	11.7	.0077	- .037
36		0	10	-10	0.275	.0260	10.6	.0069	- .046
37		0	10	0	0.271	.0270	10.0	.0060	- .046
38		0	10	10	0.264	.0280	9.4	.0042	- .044
39		0	20	10	0.224	.0240	9.3	.0043	- .029
40		0	20	0	0.251	.0270	9.3	.0043	- .047
41		0	20	-10	0.240	.0240	10.0	.0047	- .033

Table 3 - Continued Next Page

Table 3 - Continued

No.	α^o	x	y	z	C_L	C_D	L/D	C_ℓ	C_M
42	4.28	∞	∞	0	0.265	.030	8.8	.0026	- .044
43	5.17	∞	∞	0	0.320	.037	8.7	.0027	- .052
44	6.05	∞	∞	0	0.386	.044	8.8	.0035	- .070
45	7.13	∞	∞	0	0.458	.058	7.9	-	- .076
46	3.30	80.3	0	-10	0.333	.028	11.9	.0148	- .065
47	↓	80.3	0	0	0.314	.028	11.2	.0090	- .055
48	↓	D A T A G A R B L E D							
49	↓	80.3	5.5	-10	0.306	.029	10.6	.0141	- .044
50	4.28	80.3	5.5	-10	0.341	.030	11.3	.0064	- .049
51	↓	80.3	5.5	0	0.355	.035	10.1	-	- .062
52	↓	80.3	0	0	0.370	.034	10.9	.0093	- .054
53	↓	80.3	0	-10	0.393	.035	11.4	.0148	- .076
54	5.17	80.3	0	-10	0.455	.043	10.6	.0129	- .083
55	↓	80.3	0	0	0.418	.041	10.2	.0083	- .078
56	↓	80.3	5.5	0	0.392	.040	9.8	.0071	- .070
57	↓	80.3	5.5	-10	0.382	.035	10.9	.0069	- .055

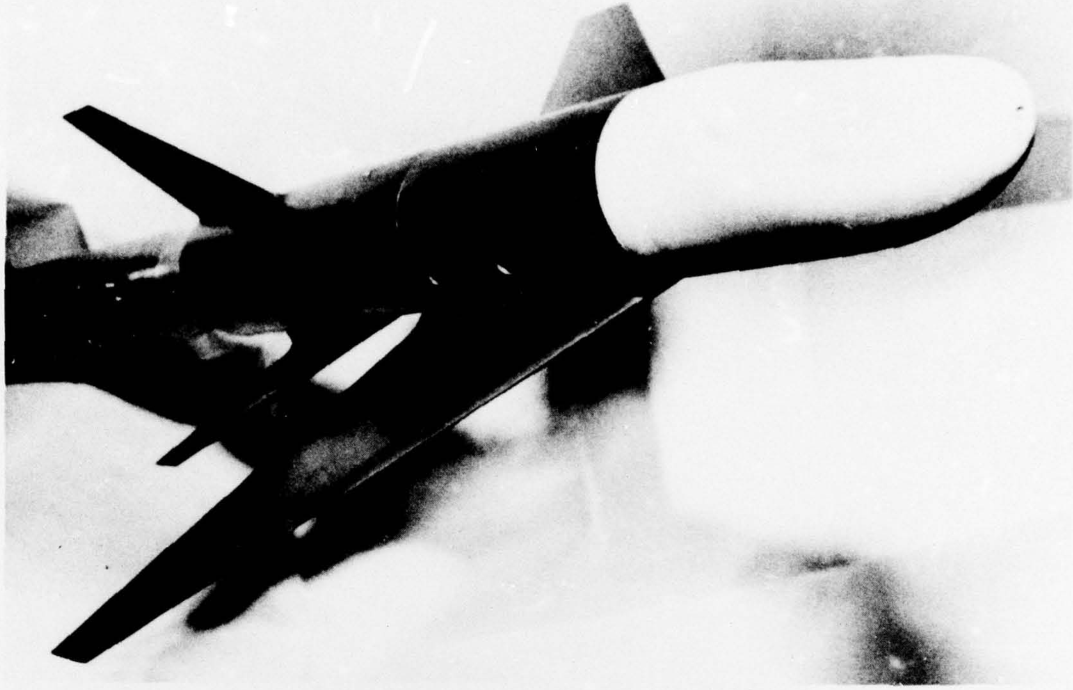
Notes: x is the downstream distance from the tip of the Boeing 747 wing to the tip of the small aircraft wing in feet, full scale.

y is the lateral distance tip to tip, and

z is the vertical displacement of the wing tips; positive values indicate the small aircraft is above the Boeing 747.

C_ℓ is the rolling moment coefficient taken about the body axis.

C_M values are referenced to the quarter chord point of the wing mean aerodynamic chord.



SMALL AIRCRAFT MODEL

MODEL OF BOEING 747 AIRCRAFT

FIGURE 1 - PHOTOGRAPHS OF THE TWO AIR CRAFT MODELS

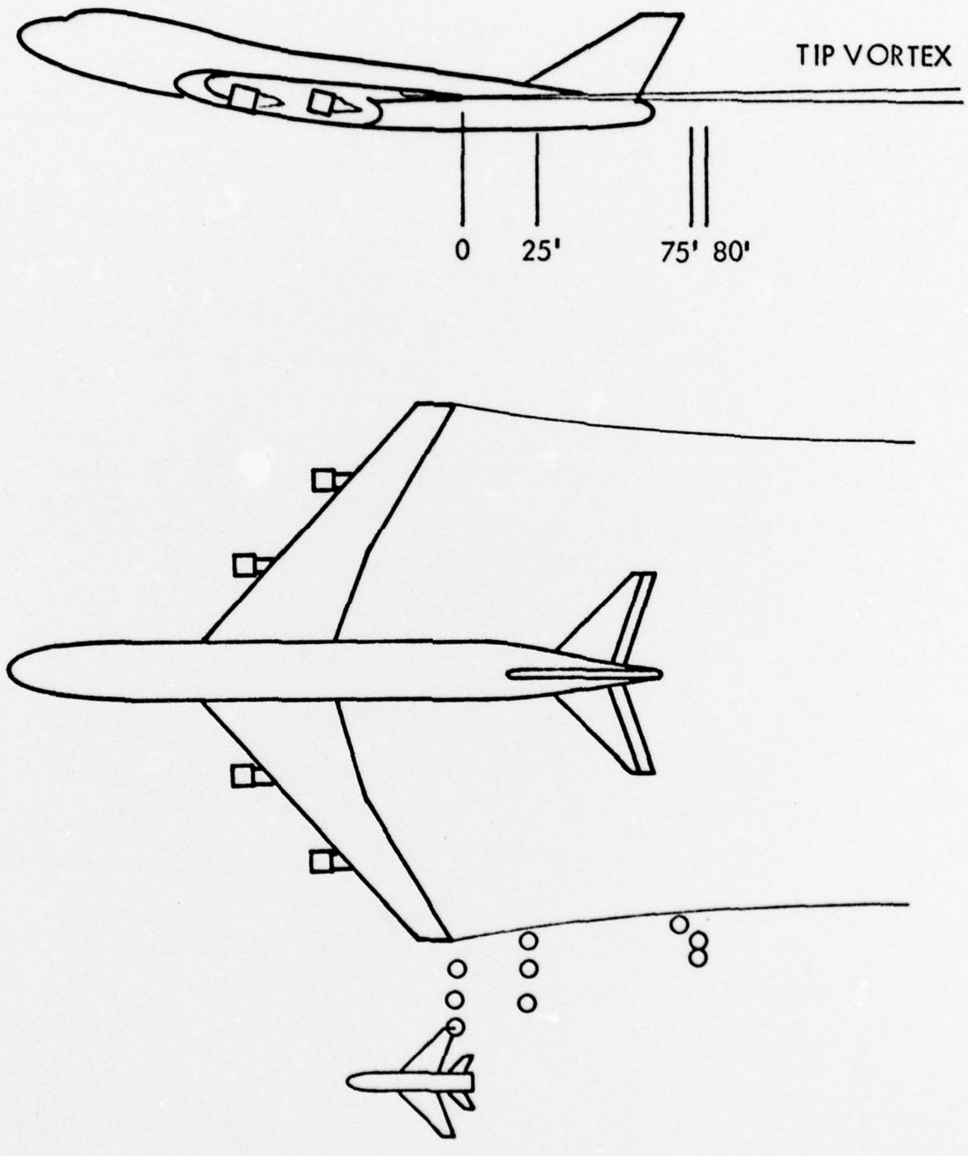


FIGURE 2 - GEOMETRICAL TEST CONDITIONS

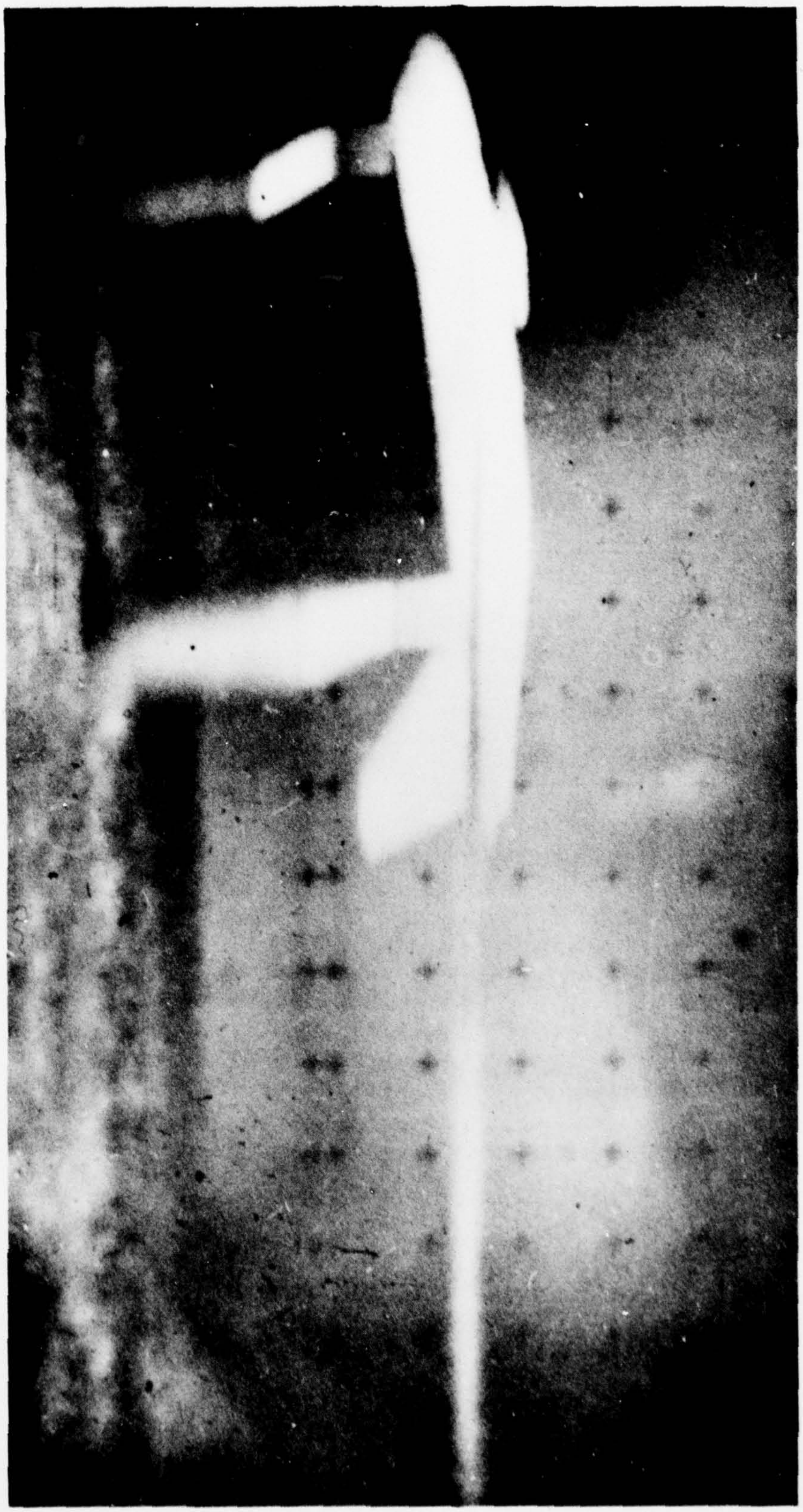


FIGURE 3 - DYED VORTEX SEEN AGAINST THE REFERENCE GRID

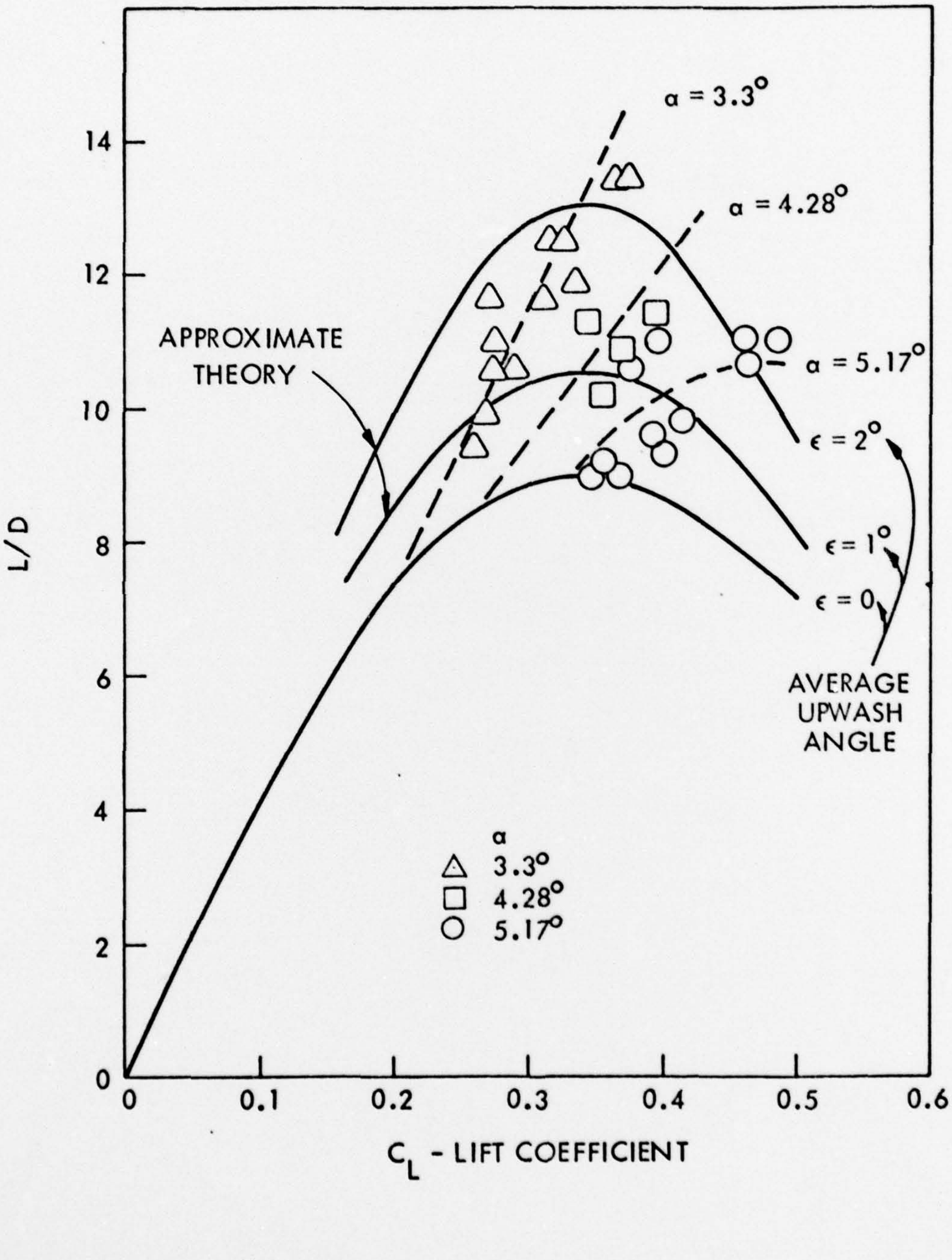


FIGURE 4 - COMPARISON OF LIFT TO DRAG RATIO DATA WITH APPROXIMATE THEORY

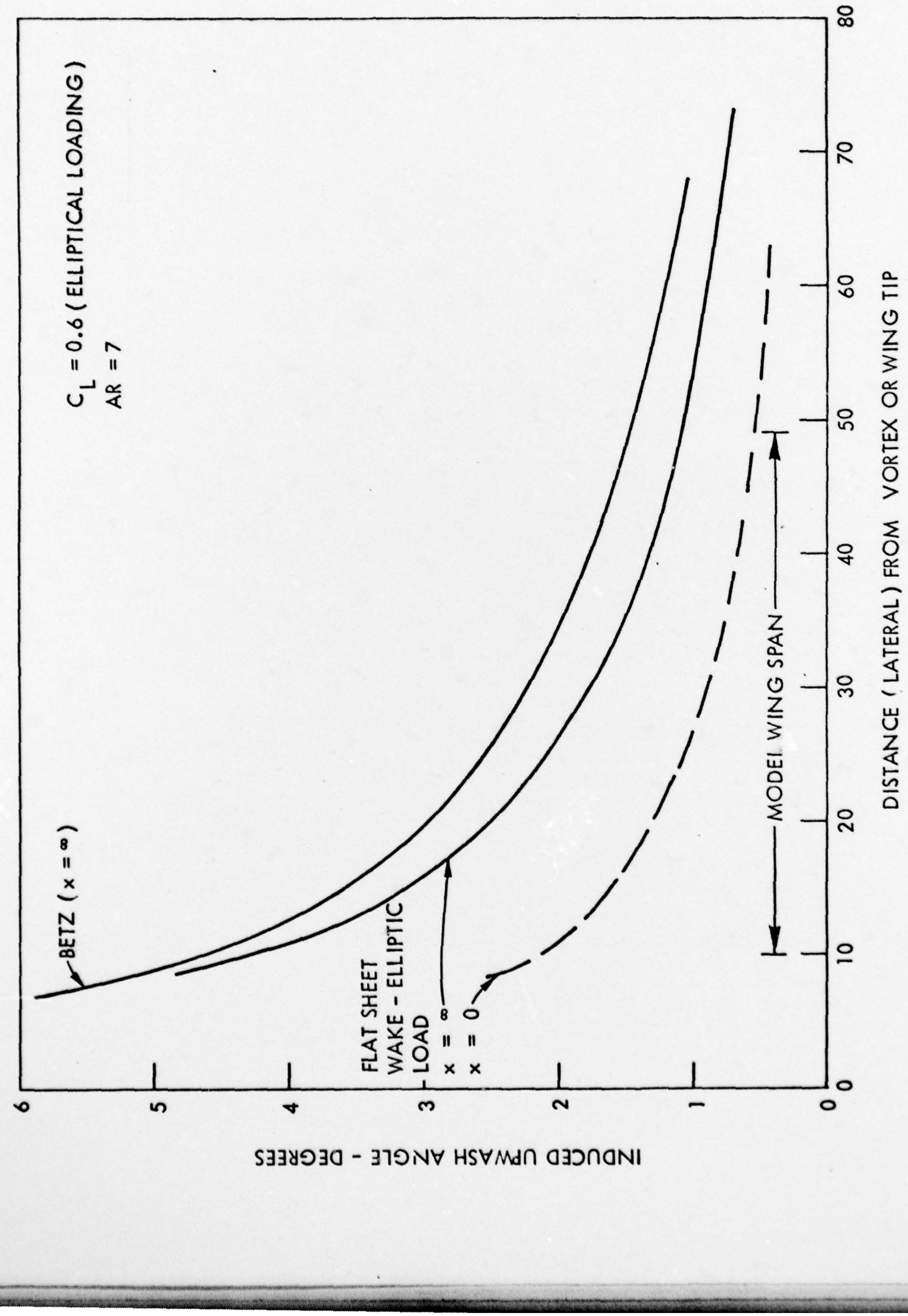


FIGURE 5 - VARIATION OF UPWASH WITH LATERAL POSITION

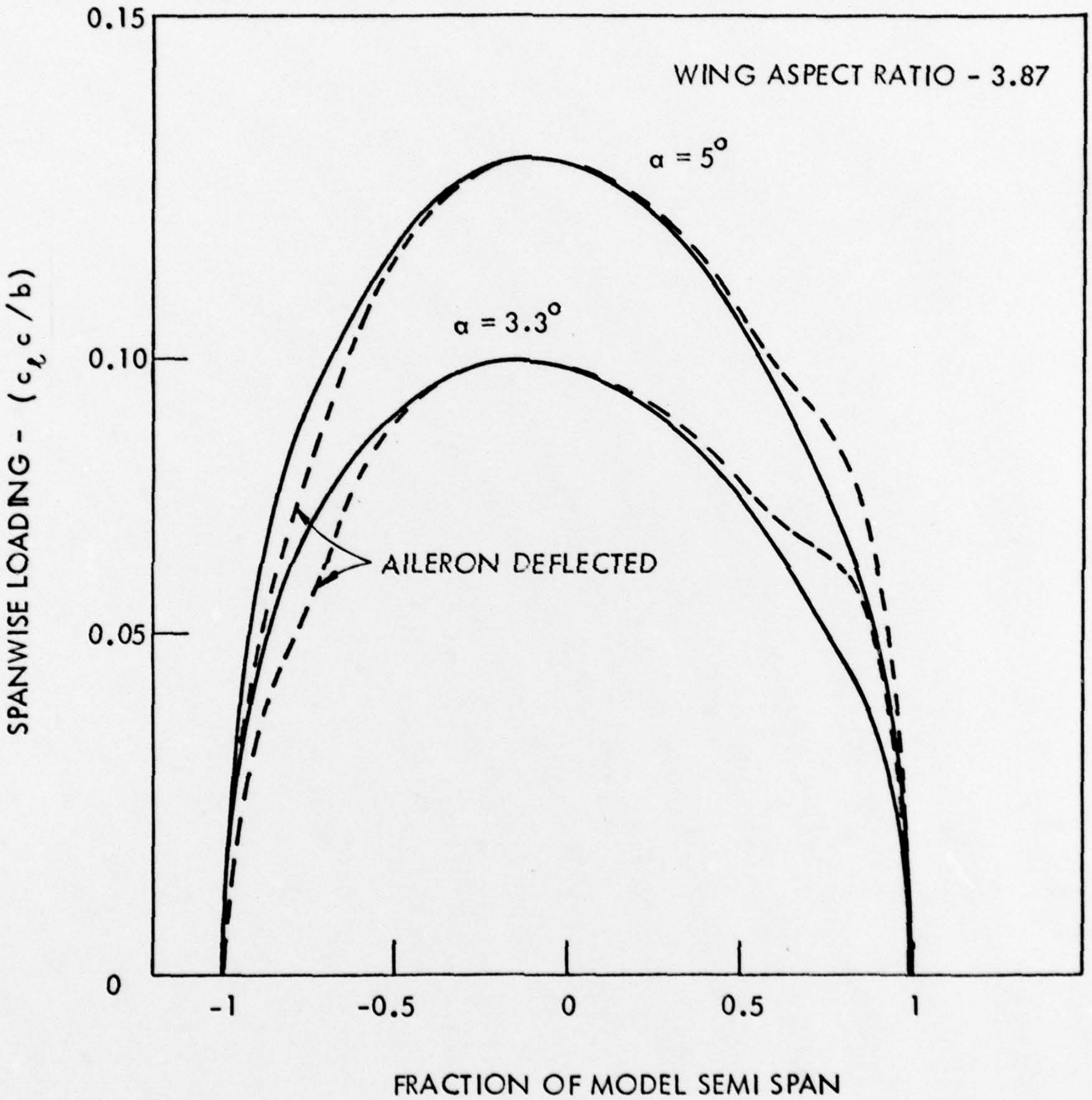


FIGURE 6 - SPAN LOADING WITH AND WITHOUT AILERONS SET FOR ZERO ROLLING MOMENT

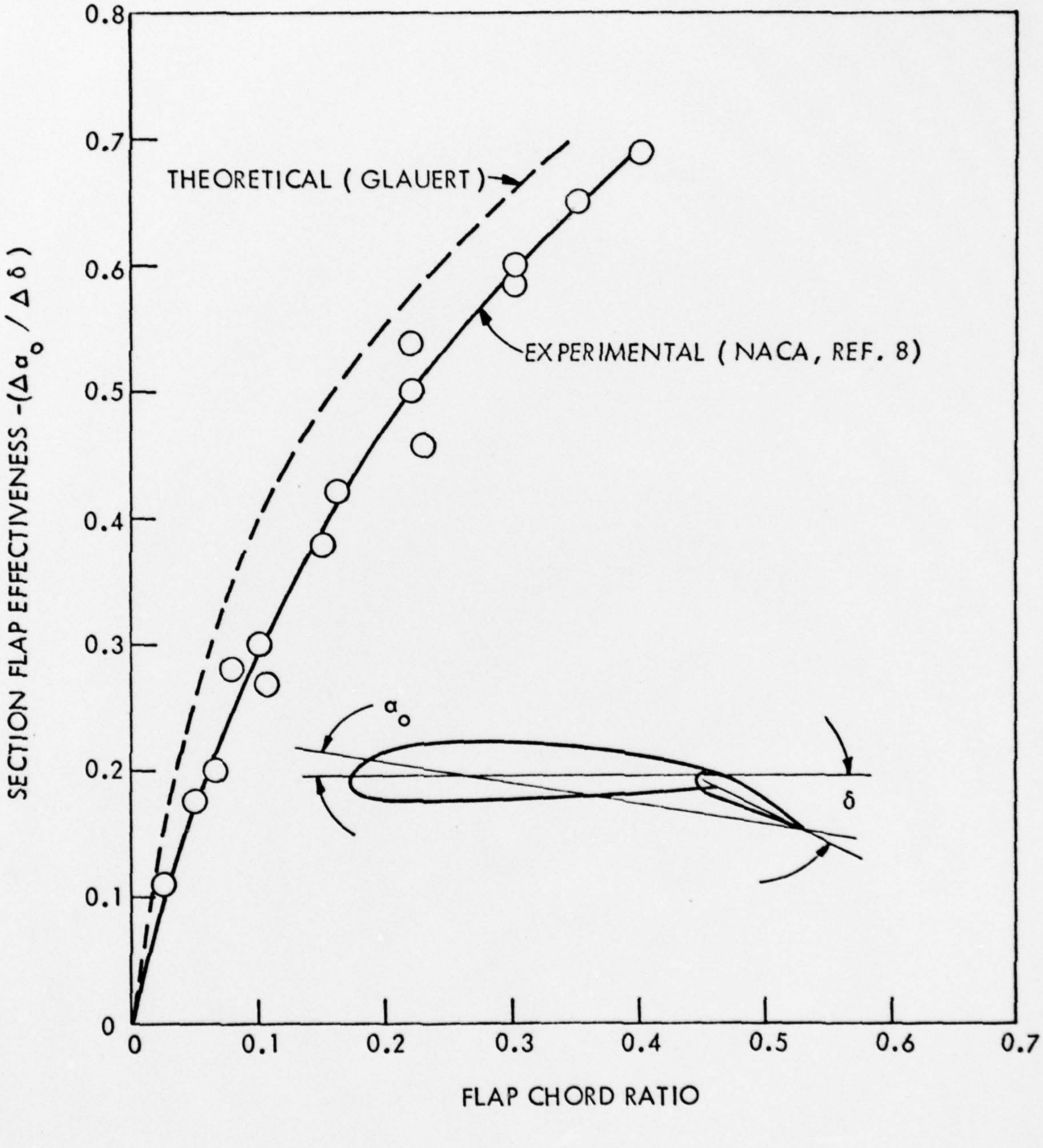


FIGURE 7 - AILERON DEFLECTION BASE DATA

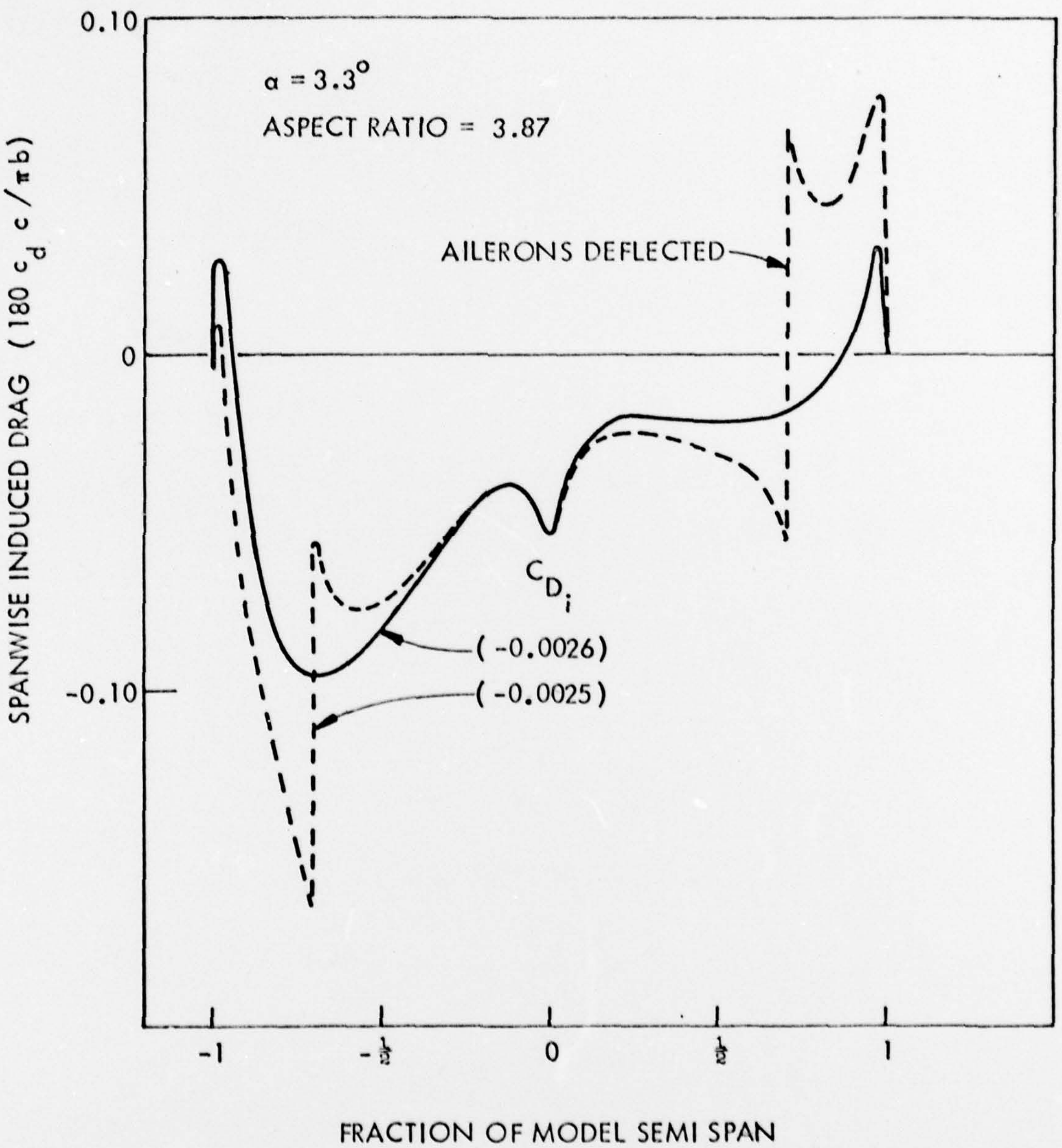


FIGURE 8a - DISTRIBUTION OF INDUCED DRAG ALONG WING SPAN

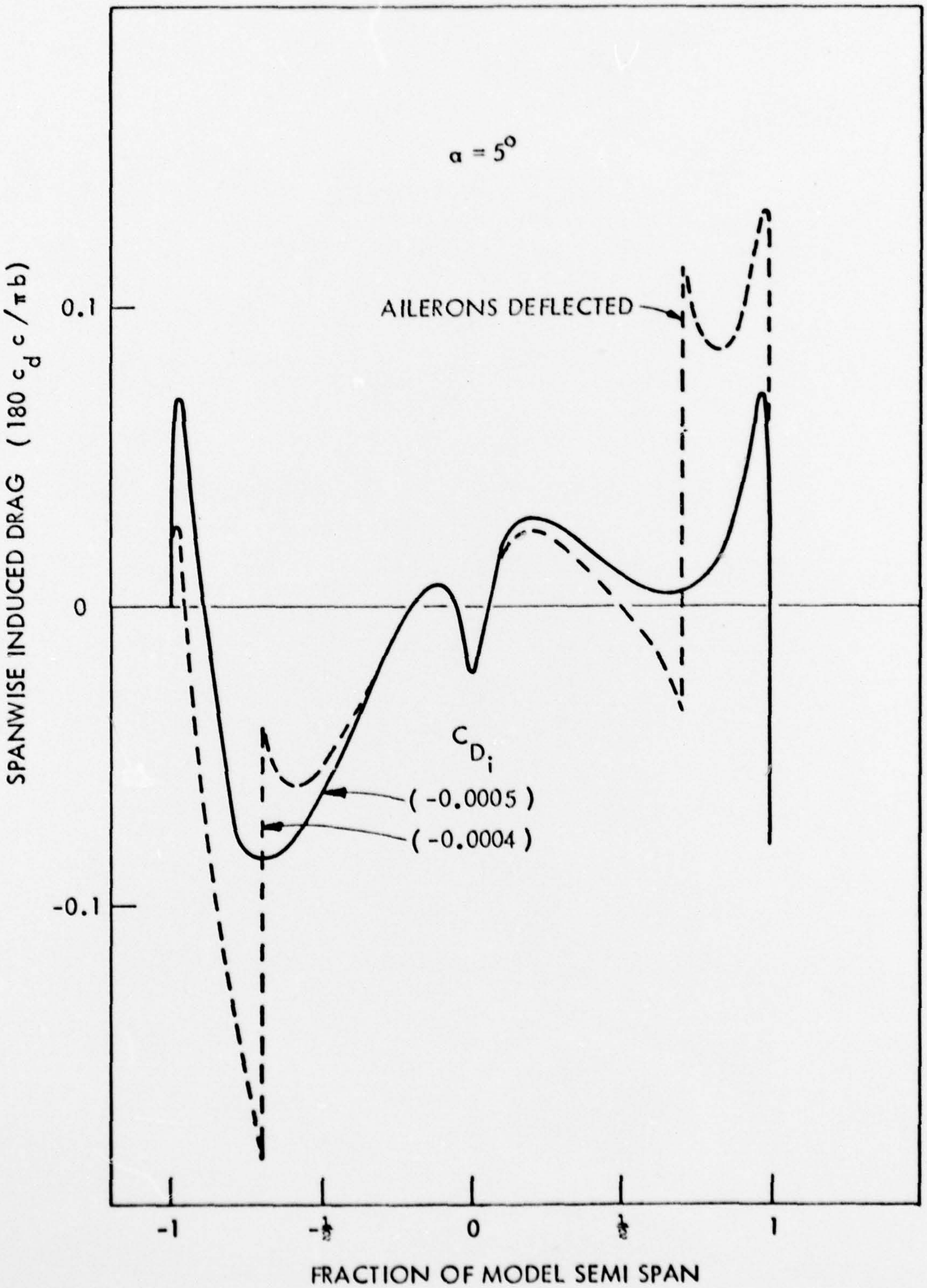


FIGURE 8b - CONCLUDED

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A study has been made of the forces and moments acting on a small aircraft while it is flying in the upwash field adjacent to and behind the wing tip of a larger airplane. Preliminary analysis of the expected ranges of forces and moments were made using available theoretical methods and confirming experiments were performed in the HYDRONAUTICS Ship Model Basin. The tests ~~utilized~~ a large model of the Boeing 747 transport aircraft and a smaller model typifying a fighter-type aircraft. The range of positions of the small model relative to the large model extended laterally 30 full-scale feet from the wing tip or from the tip vortex and downstream roughly 80 feet behind the

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wing tip. Consideration was given to the problem of maintaining steady position at a point that provided a maxmimum increase in the lift to drag ratio (L/D) of the small aircraft. The model tests have shown that an increase of 50% ~~percent~~ in ~~lift to drag ratio~~ can be obtained by a small fighter-type aircraft flying close to the tip trailing vortex of a larger aircraft. Higher increases in ~~lift to drag ratio~~ (L/D) for the same relative aircraft positions would result if the smaller aircraft exhibited higher performance (maxim L/D was 8.9 in free air). Calculations made for the models tested indicate that control power of typical fighters would be sufficient to maintain level flight in the favorable positions close to a tip vortex. No influence of the small aircraft on the large should be felt because the most favorable locations for the small aircraft are well behind the wing tip of the large aircraft.

(L/D)

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